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# **Mathematical and Computer Modelling of Electro-Optic Systems using a Generic Modelling Approach**

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## **ABSTRACT**

The conventional approach to modelling electro-optic sensor systems is to develop separate models for individual systems or classes of system, depending on the detector technology employed in the sensor and the application. However, this ignores commonality in design and in components of these systems. A generic approach is presented for modelling a variety of sensor systems operating in the infrared waveband that also allows systems to be modelled with different levels of detail and at different stages of the product lifecycle. The provision of different model types (parametric and image-flow descriptions) within the generic framework can allow valuable insights to be gained.

**Keywords:** Electro-optic sensor system, infrared, generic model, computer simulation

## **1.0 Introduction**

In the application of modelling and simulation techniques models are often created on a one-off basis for a specific task. In industry, new designs of engineering systems, similar in many ways to earlier systems, often spawn completely new models [1]. Also, these models are seldom validated or adequately documented. A poorly-documented model of questionable validity is unlikely to be widely used, let alone re-used. This paper outlines an approach to the development of generic models for electro-optic systems. The approach encourages re-use of models and offers a rigorous approach to validation and documentation.

## **2.0 Electro-optic systems**

Electro-optic (EO) sensors convert photons into electrical signals. They are used within EO systems for imaging and different technologies allow operation of EO systems over the ultra-violet, visible and infra-red wavebands. Applications include Infra-Red Search and Track (IRST) systems, Missile Warning Systems (MWS) and Thermal Imager (TI) systems.

EO sensor systems involve a number of elements, including the scanning and steering devices, optical components, a detector (with associated readout electronics hardware) and signal processing hardware and software. Elements to be modelled may include non-linear dynamic systems (e.g. target motion); atmospheric effects such as attenuation; optical and detector elements; electronic circuitry and associated noise sources; the signal processing system; and the display system (including elementary eye-brain system modelling in some cases). Figure 1 shows a basic, simplified EO system block diagram.

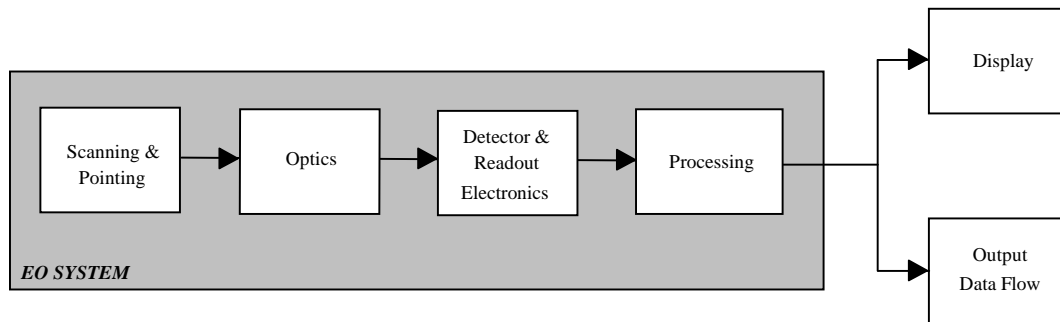


Figure 1. Basic electro-optic system block diagram

## 2.1 Performance assessment in electro-optic sensor systems

Determining the performance of an EO sensor system directly is a difficult, time-consuming and often costly exercise. The functional performance of individual components of the system can often be quantified under laboratory conditions but the overall performance of the complete system can seldom be assessed in that way. Performance tests on a full system usually require field trials on production or pre-production equipment. Design problems highlighted by trials may demand costly reworking and further trials. It is also noted that trials may cover only part of the operational envelope of the equipment and so successful completion of trials does not imply a problem-free system.

Field trials involve creating scenarios of interest to assess the performance in different conditions. Such testing requires careful timing of sensor, target and scene object movements as well a possible decoy and countermeasure deployment for military applications. Weather conditions may provide a further difficulty in that the weather experienced in trials may not be the conditions within which the sensor must operate.

## 2.2 The role of modelling and simulation

Mathematical modelling and simulation can address some of the above problems and help to fill the gap between design and the realities of the system performance. Modelling has many functions. For EO sensor systems, a model has a number of possible benefits, including an early assessment of overall performance within or beyond the normal operating envelope, and insight into parameter dependencies and sensitivities which can help in design optimisation and minimise design re-work.

Two broad classes of model are commonly used in the EO systems field. These are traditional *parametric* models and *image-flow* models [2]. Parametric models can characterise a given system using a relatively small number of key quantities and establish relationships in terms of couplings and inter-dependencies. Image-flow models describe the effect of EO system elements in terms of images at each stage of the processing chain [3]. Such models allow the effect of optical aberrations and noise sources to be seen rather than to be described mathematically. One advantage of image flow models is that they provide a convenient test-bed for signal processing algorithms.

### **3.0 The concept of a generic sensor model**

The potential benefits from adopting a more generic approach to the modelling of EO systems are considerable. Speed of development of new models is possibly the greatest benefit, along with the associated cost savings. Establishing the validity of a complex model in clearly defined steps is another, because this allows model results to be used with greater confidence. Furthermore, traceability and inheritance problems are removed by introducing a generic framework and wasteful duplication of effort can be avoided [1].

The term ‘generic’ is defined, for the purposes of the work described here, as ‘general, not specific or special’. In the case of EO systems, the similarity of the fundamental components that constitute a system (optical chain, detector, electronics, processing and display, as shown in Figure 1) provide the basis for the generic representation. From this generic architecture all specific EO systems can be derived [2,4-7]. Similar approaches involving generic models have been adopted in other fields of application such as gas turbines [8] and power electronic systems [9]. In the last of these application areas (power electronics) the central importance of models and the potential benefits of using standard building blocks [10] in the development of future systems is receiving particular attention [9]. More general issues associated with model re-use, which is of central importance in generic models, have been raised in other recent publications (e.g. [11]).

A Generic Sensor Model (GSM) must have a flexible architecture so that different system types may be represented. Although this must be detailed enough to allow some variations between systems, sub-systems or components to be modelled, it must allow a clear understanding of a model’s design and permit rapid reconfiguration. Categorising EO system components to enable any EO application to be described requires an in-depth understanding of real systems. Also, the requirement to describe the EO system with varying degrees of complexity further complicates the design of the generic model.

The methodology has developed through a series of manageable steps in which a highly flexible GSM was created in parallel with more specific models for particular types of EO system. The first of these examples involved a Thermal Imaging (TI) system. The complete process of building up the GSM was termed a “waterfall” cascade process in which the full generic functionality of the GSM was added to in stages and proven in each instance via a specific modelling example of a real system. This growing “waterfall” allowed the GSM development to be robust and the risk of

the development process to be minimised. Figure 2 illustrates the “waterfall” cascade process.

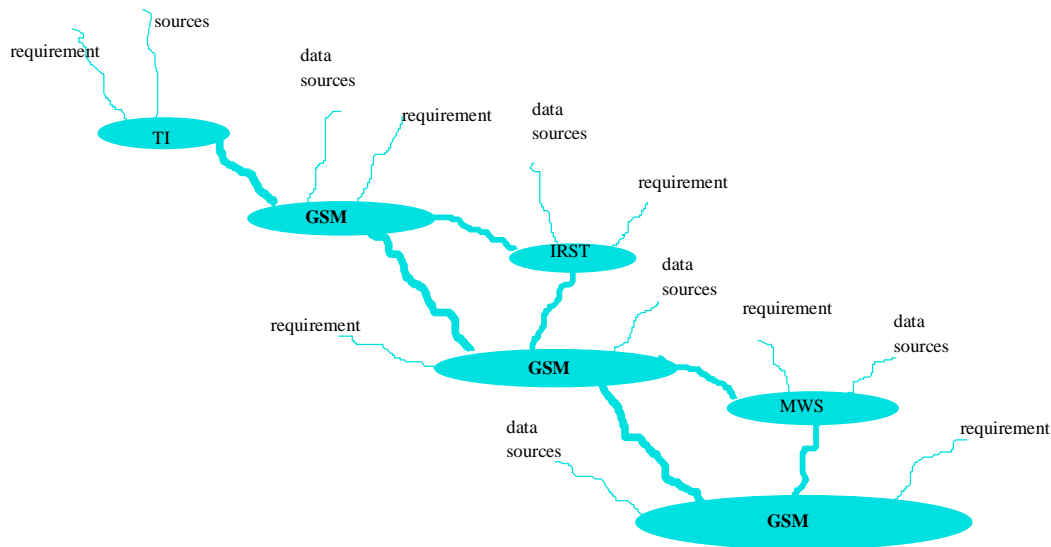


Figure 2. Schematic diagram illustrating approach to generic sensor modelling based on the “reservoir” structure and involving creation of models of specific sensor systems (a Thermal Imager system (TI), an Infra-Red Search and Track system (IRST) and a Missile Warning System (MWS)) in parallel with the generic sensor model (GSM).

Initially, the generic model was validated against real data for a specific thermal imaging system [4]. The second stage involved adding to the functionality of the generic model with additional elements for Infra-Red Search and Track (IRST) systems [4,5,6]. Once again the generic model was configured to represent a specific system so that it could be validated. The same approach of deriving a specific model from a generic framework, validating it against real data, and then integrating new component models back into the generic sensor model was applied again with a Missile Warning System (MWS) [4,7].

This approach has a number of advantages. Firstly, it breaks the problem down into a number of parts. By developing models of specific systems in parallel with the development of the generic model, confidence may be established and new modules within the GSM structure can be added with the full knowledge of the behaviour, sensitivities, error bounds and interfaces required. As the GSM becomes larger, the need to avoid changes to its structure becomes more and more important. Risk is further minimised by the iterative nature of the approach.

Another feature of this approach is that it provides a solution to the problem of how to validate a generic model. Although the full GSM cannot be completely validated, specific configurations of the model can be tested, as can most modules within the generic description. To validate individual modules and specific configurations representing particular EO sensor systems, an appreciation of the model’s strengths and weaknesses can be built up together with an understanding of sensitivities and the valid operational envelope.

Modifications to the generic model can be tested immediately, through regressive testing methods analogous to those used in software code testing, for specific model configurations that have been tested earlier. The investigation of new EO system configurations, not already considered in terms of the generic model, force the re-use of sub-models and test the generic philosophy repeatedly. If, at any stage, it is found that the approach fails, then either a fundamental design flaw will have been exposed in the model or a limitation will have been found in the generic approach. Detailed issues of testing and validation of the generic model are discussed more extensively in an associated paper [12].

#### **4.0 A methodology and design for a generic electro-optic sensor model**

The approach taken was based on simplicity and modularity. Achieving a simple design in a model of this kind is not easy, given the complexity of the problem, the numerous EO applications to be represented and the varying levels of model detail to be included. However, a simple model design was seen as essential in order to create a truly generic description for a variety of applications.

##### **4.1 Software tools and the design approach**

Selective use of software engineering tools assisted in the design process. A balance was struck between stringent software engineering practices developed for safety-critical software and the less structured approach generally taken to simulation. The number and variety of the GSM requirements imposes significant demands and requires a software tool to manage, analyse and consolidate requirements. The software package RTM (Requirements Traceability Management) [13] was selected for this task. The nature of the GSM lends itself to a top-down functional approach and the analysis and design tasks were undertaken using Teamwork [14] which implements the Yourdon [15] methodology. This tool provides a traceable path for design changes and although it provides much information about a system there are elements missing, such as a mechanism for describing timing information or time-dependent behaviour in the system. However, the Yourdon methodology was adopted for the GSM because no approach was identified that could fully describe all aspects of a system design and time-dependent performance was not an important aspect of this application.

##### **4.2 Requirements engineering**

*Requirements engineering* is a term used to describe the process of defining of requirements for a software system and the analysis needed to produce a software specification. It should provide a reference point for the whole design and helps to ensure that software will be easy to modify.

Every requirement is defined by a clear statement of need and is numbered and cross-referenced. In some cases requirements definition and analysis tasks may be augmented by diagrams known as *conceptual models* [6], which illustrate the main operations of a system.

Once a set of requirements has been established it needs to be validated to reduce the risk of costly errors being introduced at the start of the design process and propagating

through the lifecycle of the software. The principles of requirements testing and validation are based upon testing, verification and validation principles that apply generally within software engineering.

The aims and objectives of the GSM were expanded into a set of specific requirements involving a) the model functionality, b) the software tools and framework, c) input and output quantities, d) operational scenarios, e) interfaces, f) documentation and g) model version control.

### 4.3 Design levels for the generic model

The GSM design comprises functional and processing representations of the system as well as data flow, logic flow and screen definitions. Figure 3 shows definitions for the architectural layers and terms. The process of establishing levels in this way has been termed *design levelling*. This provides a means of relating the many individual mathematical models developed for the GSM to each other and mapping them on to a single, consistent, architectural design. Once consistency has been established across the model, different elements at the same level have the same depth of design detail. This is an iterative process since the need for a particular level of detail within a model may increase or decrease as the architectural design progresses. As illustrated in Figure 3, five levels of software were defined for the GSM and these are as follows:

- |                          |                                                                                          |
|--------------------------|------------------------------------------------------------------------------------------|
| • Context Level          | - Defines the environment for the GSM.                                                   |
| • Functional Block Level | - Establishes groupings of functionality.                                                |
| • Module Level           | - Provides a collection of linked design features within each functional block           |
| • Unit Level             | - Each module is divided to a level where the operations can be identified clearly.      |
| • Component Level        | - Each component corresponds to the detailed design description of a task within a unit. |

#### 4.3.1 High-level design

The high-level functional design of the GSM is shown in Figure 4. In Yourdon terms, the Context Diagram consists of three objects: the GSM, the User and External Models and Simulations. The GSM comprises seven functional blocks and incorporates the graphical user interface.

The first functional block is *System Configuration*. Two models constitute this functional block. The *Run Editor* controls the specifics of the run and the *System Configuration Editor* assembles the necessary GSM models to fulfil the demands of the Run Editor.

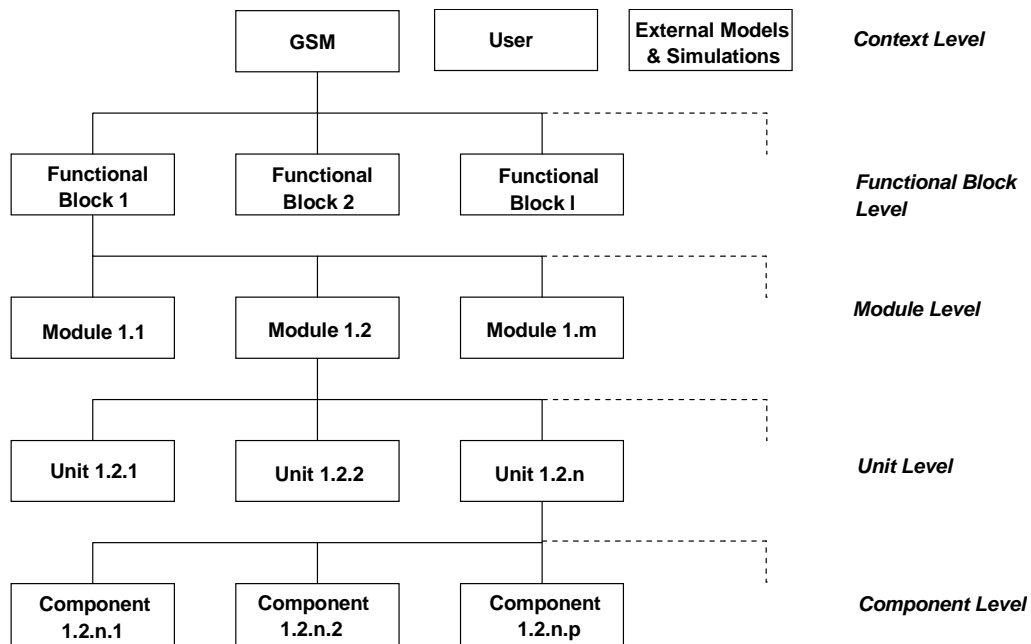


Figure 3. Design terminology definitions for the generic sensor model

Automatic checks are carried out by the *Data Checker* block before a run starts. Simple checks, such as data input type and range, are performed by the *Data Format Checker*. A more thorough check is performed by the *Data Consistency Checker* which verifies that all of the data entered are self-consistent and compatible for the specified run. Any response from these two modules would be determined by the *Data Response Formatter*, which provides error messages or warnings.

The two main functional blocks of the GSM are the *Parametric Model* and the *Image-Flow Model*. Both provide three levels of complexity or *Tiers*. In general, Tier 1 level models are used for concept design, have the least mathematical detail and can incorporate approximations, simplified equations and rules of thumb. They offer a fast route for generating performance estimates. Tier 2 level models include more detailed mathematics and provide an intermediate-level sensor system model based on design information typically available during the initial design phase. At Tier 3 level there is a rigorous mathematical treatment of the components modelled and this leads to a detailed (high fidelity) sensor system model based on design information available during and after the detailed design phase.

The Parametric and Image-Flow Models share a common high-level design. This is because they are different representations of the same EO systems and functions. A Parametric Model may be a series of transfer functions and equations that correspond to a statistical description of the behaviour of the system. An Image-Flow Model simulates the processes within the EO system by implementing signal and image processing algorithms and produces images as its output. It is appropriate to have cross-coupling links between the Parametric and Image-Flow Models so that results of calculations within one model type can be passed to the other, for use as an input or simply to be displayed as an output. One example of this cross-coupling is the extraction of scene metrics (e.g. clutter statistics from real data) from the image-flow model for use in the parametric model. Another example is calculation of the optical



blur in a system by the parametric model so that it can then be applied to a scene in the image-flow model to provide visualisation of the degradation.

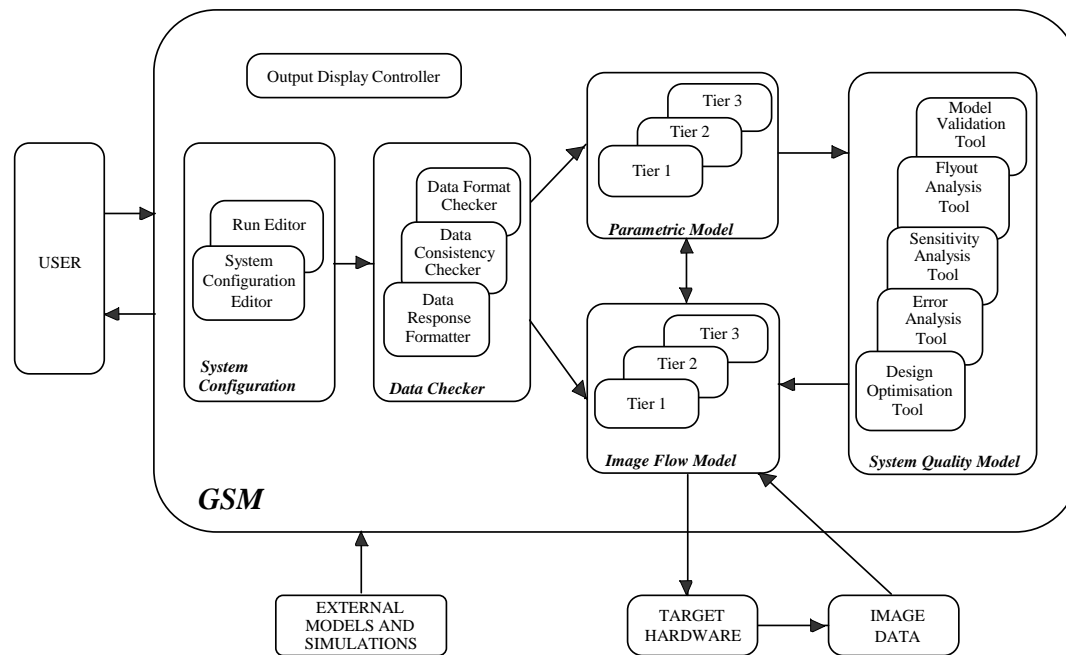


Figure 4. High-level design of the generic sensor model

Requirements in terms of the analysis of model results have been addressed in the design of the GSM by including a *System Quality Model* which involves five modules: *Design Optimisation*, *Sensitivity Analysis*, *Error Analysis*, a *Fly-out Analysis Tool* and a *Validation Tool*.

The *Design Optimisation* module allows the user to search for the optimum design solution based on a given starting configuration. It should allow an EO system design to be formulated using the configuration and data bounds specified by the user. A variety of search strategies can be used.

The *Sensitivity Analysis* module automatically examines the stability of a system design with respect to environmental variables, system variables or component degradation effects. The *Error Analysis* module builds upon the Sensitivity Analysis module output information to provide an indication of the errors associated with model results for given levels of uncertainty in terms of system variables and components.

The *Fly-out Analysis Tool* allows the GSM to carry out Operational Analysis involving Monte Carlo simulation studies. Such studies help in establish appropriate operating environments for the sensor system.

The *Validation Tool* allows model results to be compared with measurement data on file. This module produces a number of metrics that quantify the validity of the model over a specified operating range.

There are two further functional blocks within the GSM. These are the *File Manager*, which provides all of the default parameters from files but is not shown in Figure 4, and the *Output Display Controller*, which is included in the block diagram and handles all aspects of display formatting of output data. Finally, links are provided to allow hardware-in-the-loop testing in association with the image-flow model.

### 4.3.2 Parametric model design

The parametric model involves four modules. These are the *Environment* module, the *Sensor Head* module, the *Target Processing* module and the *Display and Human Interface* module and they are linked in a sequential manner, as illustrated in Figure 5.

The shaded bands in Figure 5 represent the four modules specified above and the blocks underneath are the units that make up each module. A user is given the option of by-passing one or more units or modules when specifying a run, provided the action is permissible. Data for each unit may be entered by the user or default values may be chosen.

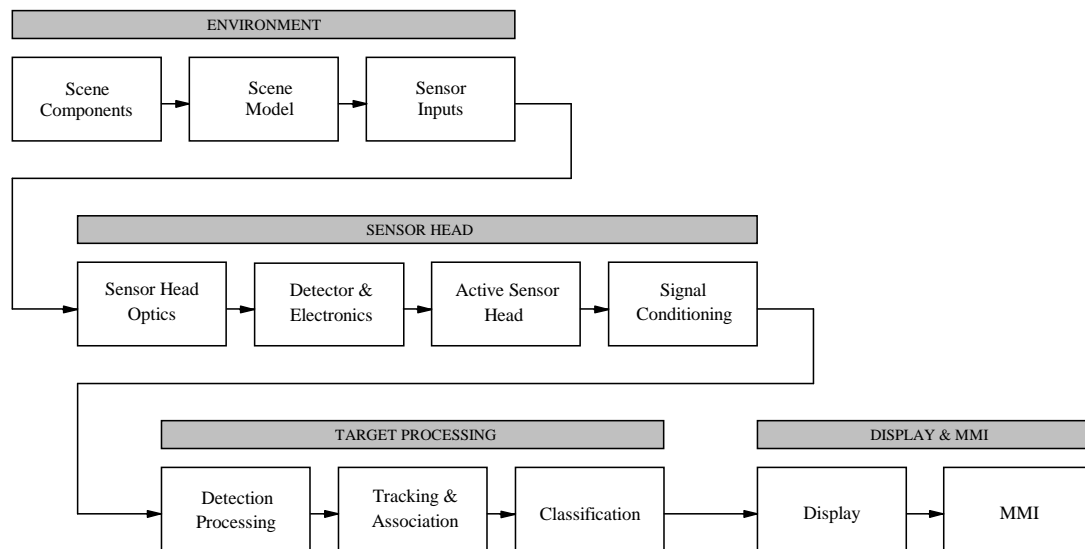


Figure 5. Architecture of the parametric model

### 4.3.3 Image-flow model design

The high-level architectural design of the image-flow model is identical to the design for the parametric model. This allows the commonality between the models to be exploited and code to be re-used as much as possible. It also provides a one-to-one mapping, which helps in testing, internal verification and external validation. However, at lower levels in the design, greater interaction of components and feedback of data is possible in the image-flow model and is a requirement of many of the processing algorithms.

The use of valid input data is as important for the image-flow model as it is for the parametric model, but the image-flow model input data is generally more difficult to obtain. An image-flow model is used to test the performance of image processing and tracking algorithms and the demanded level of scene realism (in terms of radiometric

accuracy) for good performance prediction is extremely high. The most accurate performance figures will be achieved by using real data recorded by an EO system. That imagery would serve as input data directly to the Processing Module of the GSM since it would already contain all of the atmospheric and sensor effects within it. Synthetic images produced by the image-flow model must be based on the analysis of real data of this kind.

#### **4.3.4 Graphical user interface design**

One important element of a user-friendly generic model is the user interface and an early decision was taken to implement a graphical user-interface (GUI). Any GUI should be tailored to the needs of the user. This usually means that technical aspects of the software are hidden from the user but in the case of mathematical models this is less likely to be the so as the models will be run generally by expert users. The GUI is linked closely to the design and optimisation of the model itself because changes to the structure and content of the GSM are likely to require changes to the GUI.

The approach taken to GUI design to minimise design re-work was to separate it from the main model. Screens were not implemented until there was some stability in the model design and sets of input and output parameters had been established.

#### **4.4 Implementation**

The GSM allows ideas and designs to be developed and tested. Its principles are independent of software and hardware restrictions and should still be applicable when new generations of computers and software environments become available.

The main criterion for the GSM software coding language and environment was that it should have a powerful mathematical and processing capability and have a large user community so that the GSM would be widely accepted, understood and supported. Speed of calculation was not, however, seen to be a critical driver because the model need not run in real time.

A personal computer (PC) based package was chosen because of the processing capabilities now afforded by such machines and their wide availability. Several software packages were reviewed and a sub-set was assessed against specific criteria for the GSM. The choice of development environment and language of the initial GSM implementation was MATLAB. Although a number of other products gave better performance for certain types of modelling task (e.g. image processing) MATLAB was judged to give the best overall solution. Factors of particular significance include the large set of in-built functions, the multi-platform nature of the product and its ability to generate C code for applications for which processing speed is an issue.

## **5.0 Parametric and image flow modelling examples**

### **5.1 Parametric modelling examples**

The automatic detection of targets by an EO system and the subsequent processing to classify, track and prioritise them is a complex procedure that involves the interaction of a number of different real-time algorithms and optimised filters. Modelling such a processing chain in a parametric sense is important for examining couplings and interdependencies and for establishing key relationships. In simple terms, a target is detected using some filtering mechanism with a thresholding scheme. Following further signal processing it may then be declared as a threat and tracked before being classified.

Detection requires the separation of target and background signals through filtering. Modelling of this process can be simplified by considering the probability of the target being detected, given that it has a specific signal-to-noise ratio (SNR) and that a particular threshold-to-noise (TNR) has been set. The variation of the target and background signals means that it is possible that a spike in the background could exceed the threshold, thus triggering a false alarm. The TNR is normally set to maximise the probability of detecting a target (the detection probability) while minimising the false alarm rate. The detection probability is the probability of a target being detected as a threat. This is independent of the signal processing logic implemented in the algorithm and many schemes are possible.

It should be noted that, in the modelling of different signal processing systems for detection and declaration, it is possible that the probability of declaration may be found to be larger than the probability of detection at a specific range. This depends on the signal processing schemes considered and the modelling approach used. When such a situation arises it means that, for a given declaration range, the required signal-to-noise ratio (SNR) can be reduced. This is illustrated in Figure 6, which presents a typical output from a parametric model and illustrates the variation of detection probability (dashed line) and declaration probability (solid line) as a function of range for a given set of target, atmospheric and sensor parameters.

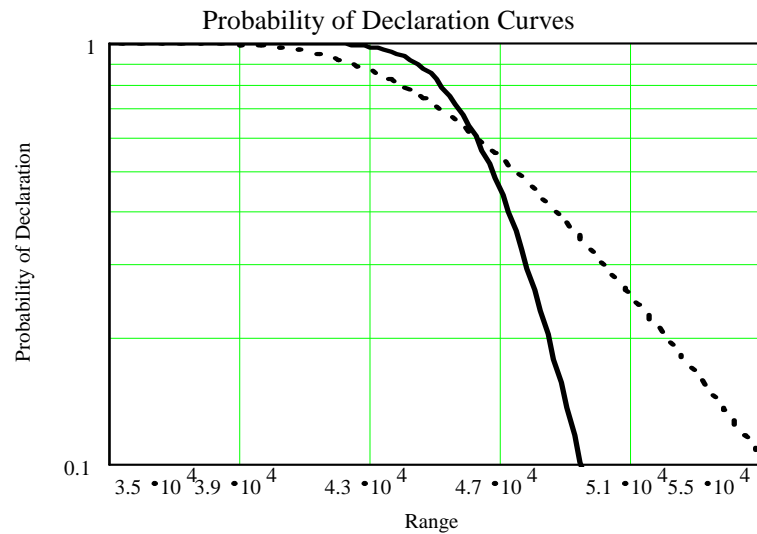
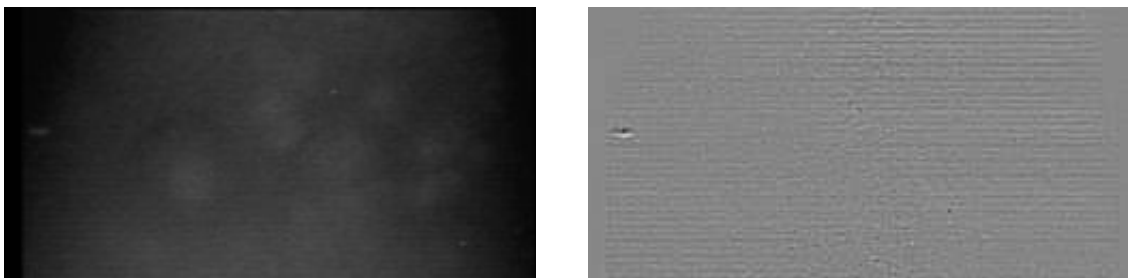


Figure 6. Parametric Model Output – The solid line represents the probability of a target being declared as a threat (declaration probability) while the dashed line indicates the detection probability.

## 5.2 Image flow modelling examples

Examples of the use of the image-flow analysis component of the GSM are illustrated in Figures 7 and 8. Figure 7 shows a poor quality thermal image which includes an aircraft that is virtually invisible. Figure 8 illustrates the effect of spatial filtering and thresholding on the image as part of the detection processing chain. Such image-processing operations can be used not only for improving the visual appearance of an image but can also provide performance data for the parametric model.



Figures 7 and 8. Image Flow Model Output: the unprocessed image is on the left while the image on the right shows the effect of spatial filtering and thresholding and indicates clearly the presence of an object (the aircraft) towards the left hand edge of the image .

## 6.0 Some examples of use of the System Quality Model

The System Quality Model involves five modules and any combination of these can be selected by the user to be included in a run. The Design Optimisation Tools and the Sensitivity Analysis Tools are particularly important and their use will be illustrated through examples.

## 6.1 Use of the Design Optimisation Tools

Most engineering design problems require optimisation in which costs and benefits are traded to allow an improved solution to be found. The first component within the optimisation module is the *Sensor Optimisation component* which is designed to perform a search over a parameter set identified by the user and return optimal parameter values for the design space specified. The second component is for *Cost Optimisation* and allows the engineering reality of a given technical solution to be reviewed by assessing the cost and risk associated with any performance gain promised.

As an example of cost optimisation consider four design parameters that could be candidates for adjustments leading to possible improvement in overall performance of an EO system in terms of signal-to-noise ratio. These could be as follows:

- Optical system performance
- Detector performance
- Electronic system bandwidth adjustments
- Signal processing performance through use of an improved clutter suppression algorithm.

Cost and risk values could be associated with each of these four design parameters and, in each case, these will be a function of the performance improvement required. For example, improvements in each of these areas could be achieved, but in most cases this could involve extra cost and risk because of the development time required and uncertainties associated with the development task. The availability of this tool should, for example, allow a manager to examine the impact of a design deficiency or provide justification for further design work.

The optimisation method is chosen from a list of candidate methods. This facility was developed as part of the GSM to establish the optimum combination of components or system parameters within pre-defined parameter ranges. A score is determined for each iteration of the model, based on a user-defined rating scheme.

Several search strategies have been assessed [2,4], including exhaustive search methods, heuristic search methods, methods based on the use of Hopfield networks (a specific form of artificial neural network) and methods involving genetic algorithms. Of these approaches the exhaustive search method was a benchmark against which other methods could be compared. Because it is so computationally intensive and time-consuming it could be used only for problems that were of relatively low complexity.

Two heuristic (rule based) search methods have been applied [2,4]. One of these was a steepest-ascent hill-climbing algorithm with enhancements (backtracking and jumping) in order to help to avoid known pitfalls of this approach. Backtracking was added to ensure that local maxima were not declared as the global maximum and a random jump was incorporated to avoid stagnation at plateaux. The second heuristic strategy searches concentric rectangular areas of interest, storing any maxima found until the limits of the search space are reached [4]. Hill-climbing or another fine

search technique can then be applied around these maxima to determine the global maximum.

A restricted data set was established to allow testing of the chosen strategies. Table 1 lists the five quantities available for adjustment and Table 2 lists five performance metrics to be optimised.

Weighting factors were applied to each parameter to indicate the level of importance placed on each. Allowable ranges for each input parameter were defined and a baseline value was set. Cost functions were also set for each input parameter to allow non-technical considerations to be taken into account in the optimisation process. Desired performance values were also specified and acceptable ranges for each were declared as constraints (Table 2).

Design Parameter Name	Baseline Design Parameter Estimate	Weighting Factor	Allowable Range	
			Minimum	Maximum
Sampling efficiency	0.8	1	0.5	0.9
Noise Equivalent Temperature Difference (NETD)	30mK	1	28mK	32mK
Effective Focal Length (EFL)	0.06m	0.3	0.04m	0.08m
Threshold-to-Noise Ratio (TNR)	5	0.5	4	6
Classifier efficiency	0.75	0.8	0.5	0.9

Table 1. Test input parameters for optimisation

Performance Parameter	Baseline Performance Estimate	Performance Requirement	Search		
			Forcing Function	Weighting Factor	Parameter Constraints
Signal-to-Noise Ratio	4	5	Proportional	0.7	min. 2
Probability of detection	0.85	0.95	Constant	0.9	0.6 - 1
Probability of declaration	0.8	0.9	Constant	1	0.6 - 1
Probability of false alarm	0.01	0.001	Constant	0.8	0 - $10^{-5}$
False-alarm rate (FAR) (per hour)	10	10	Constant	1	max. 15

Table 2. Test output goals for optimisation

An overall scoring method was used involving an objective function which considered performance demands, parametric and cost ranges, weightings and parameter constraints. Although this data set is much smaller than the set required to optimise a full EO system the search space is, nevertheless, considerable and provided a useful test of the different optimisation methods.

Table 3 provides a summary of the results for a number of techniques. Although the exhaustive search method was included it serves only to provide a benchmark against which the other methods can be compared. The table shows the maxima found by each method and the performance of each method is then compared with results from the exhaustive search. The modified steepest-ascent hill climbing algorithm performed well and found the global optimum while the second heuristic method, which was based on a concentric area search strategy and subsequent hill climbing, also performed well. The performance of the Hopfield network was relatively disappointing due to its known tendency to find spurious equilibrium states and halt on these points which are not states with minimum energy and thus do not represent the overall optimum solution [16]. Only 65% of equilibrium points found represented the global optimum, but repetition of the run many times did show that the Hopfield network could find the optimum solution reliably. The overall performance efficiency of this algorithm was thus found to be relatively poor. The genetic algorithm provided excellent results with convergence, on average, after forty generations. However, the run-time for the genetic algorithm was greater than for the other methods.



Search Strategy	Maxima Found (Top Ten)	Maximum Score (Relative)	Processing Performance
Exhaustive	100%	1	1
Heuristic Method 1 (hill-climbing with constraint satisfaction)	100%	1	951
Heuristic Method 2 (neighbour- hoods approach)	100%	1	1072
Hopfield Network	65% convergence to global maximum.	1 (with repeated runs)	26
Genetic Algorithm	Average accuracy: 91% of optimum solution .	0.91	6

Table 3. Optimisation test results

## 6.2 Use of the Sensitivity Analysis Tool

Sensitivity analysis provides a way of examining the effect of system or sensor parameters on one or more of the overall performance metrics. The *Sensitivity Analysis Tool* is designed for use together with the parametric descriptions within the GSM. Taking user-specified input parameter values the analysis tool uses the transfer functions of the parametric model to investigate variations of output parameters. Results are presented both graphically and numerically to provide an understanding of the relative sensitivities within the system.

Two separate components were designed for the toolbox: *Scene Sensitivity* and *Sensor Sensitivity*. *Scene Sensitivity* examines the sensitivity of the sensor performance to external factors such as target signal strength and dynamics while *Sensor Sensitivity* allows investigation of effects of sensor parameter variations on the overall performance.

The analysis carried out by each component is the same. The user is presented with sets of input parameters for the Tier 1 model. Any parameters may be varied by a positive or negative percentage from baseline values. Those parameters not selected for variation are held at their baseline values. All results are written to file, from which they may be retrieved and manipulated, depending on the options chosen.

Figure 9 shows typical results, in the form of a polar diagram, of a sensitivity analysis carried out to evaluate the effect of a 25% variation in radiant intensity, atmospheric attenuation, noise equivalent irradiance (NEI), detector sampling efficiency and threshold to noise ratio (TNR) on target detection probability. In this diagram dashed lines represent the nominal value (0% deviation) and the solid lines represent the variation about that value.

It can be seen from the sensitivity diagram that radiant intensity (shown on the plot by the radial line at 0 degrees) and sampling efficiency (the line at 216 degrees) have the greatest effect on the probability of detection. It can also be seen that detection of a target is less likely to be adversely affected by a change in atmospheric attenuation (the line at 72 degrees) than by an equivalent percentage change in threshold-to-noise ratio (the line at 288 degrees). It should be noted that since the nominal values in this plot all represent detection probabilities of one this sensitivity analysis is meaningful, in this particular case, for changes that reduce the detection probability.

Detection Probability Sensitivity Plot

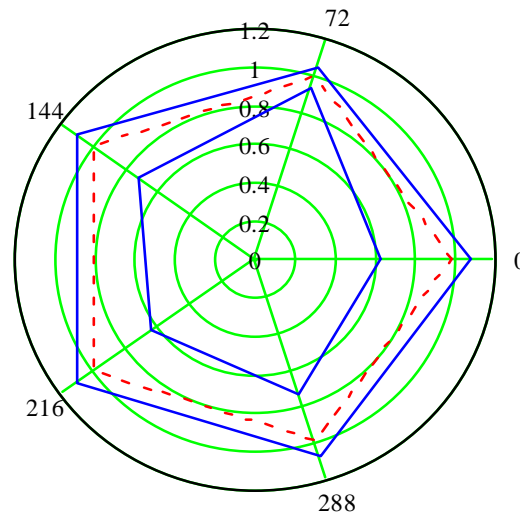


Figure 9. Example of a polar plot resulting from a detection probability sensitivity analysis. Here dashed lines represent the nominal value (0% deviation) and the solid lines indicate the variations of detection probability about the nominal value (unity) for 25% changes of each of five input quantities. The five quantities represented on this diagram are radiant intensity (on axial line a 0 deg.), atmospheric attenuation (72 deg.), noise equivalent irradiation (144 deg.), detector sampling efficiency (216 deg.) and threshold to noise ratio (288 deg.).

## 7.0 Discussion

Making a model generic in the field of electro-optic systems proved difficult. The first step was to identify the truly essential requirements and then to establish a framework that would meet these requirements whilst providing flexibility and adaptability. The third feature of the chosen approach was to make the generic sensor model concentrate on a relatively small sub-set of specific sensor systems. There are two advantages to this third aspect of the approach. While it provides concrete examples of working models that can be used to guide future developments and enhancements, it still provides considerable flexibility that can be tailored easily to the specific needs of individual programmes.

Using the generic approach, systems may be modelled at different levels of detail and complexity at different stages in the product life-cycle. A less complex model is appropriate at the preliminary design stage of a project because only rough

performance estimates are required and little information is available to allow a more detailed model to be developed. In contrast, by the end of the project highly detailed models that incorporate a large amount of design knowledge are possible and should be available to aid performance optimisation and system maintenance

The traditional engineering flow of requirements definition, top-level design, detailed design, coding, test and validation was applied to the GSM. However, the need to tailor the sequence to the needs of the model development programme quickly became evident. One of the first features to emerge was the fact that generation of the requirements definition for a generic model is a difficult task. Not only is the number of requirements very large but also many are not fully defined at the initial stage of model development and not all are of equal importance. The initial focus on a few specific systems helped considerably and allowed priority issues to be identified. The grouping of these issues and the flow-down to a structured analysis also proved to be successful because it helped to define the architecture of the model. In terms of project time-lines, the requirements analysis is not considered to be complete and is an ongoing activity. To date, all new requirements imposed on the generic model have been accommodated without difficulty.

## **8.0 Conclusions**

Mathematical and computer-based modelling has an important role in the design and development of electro-optic systems. It provides an insight into system behaviour, sensitivities and dependencies before a system is built so that its performance may be optimised and costs minimised. Computer-based modelling also enables trade-off studies to be automated and controlled and different configurations of system to be tested in safety.

The main factors of significance in the model design and implementation process include the fact that modelling must be tied to the complete project lifecycle and a set of models of different mathematical complexity is needed to fulfil the modelling needs of a project throughout its lifecycle. Also, a structured approach to requirements analysis and design is essential and the model design process should be based on rapid prototyping. It should support iterative development using appropriate software tools and a suitable environment.

Model validation issues are very important for any work involving the practical application of mathematical and computer-based models. The generic nature of the model in this case gives rise to special questions that lie beyond the scope of this paper and are discussed elsewhere [13,17].

The main conclusion is that a generic EO system model is possible. It may also be concluded that parametric representation of systems provides useful performance estimations but is limited by the statistical approach taken to the complex processing chain, while image-flow models of scenes and the EO system processing are required to fully describe the system performance, especially if real data is fed directly into the processing module of an image-flow model. The provision of these different model types (i.e. parametric and image flow) within the generic model can thus provide valuable insight that could be lacking in the absence of such cross-coupling.

Overall, a novel approach to tackling the complex problem of EO sensor systems modelling has been demonstrated successfully. The research provides a solution for the EO systems community in which modelling supports the systems engineering lifecycle and allows predictions and analysis of system performance to be made using a truly flexible and generic framework. The benefits of this approach, including design re-use and rapid development, have been demonstrated through specific case studies.

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